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Exergy analysis for unsteady-state heat conduction

Wonjun Choi [a,*], Ryozo Ooka [a], Masanori Shukuya [b]

[a] Institute of Industrial Science, The University of Tokyo, 4-6-1 Komaba, Meguro-ku, Tokyo 153-8505, Japan
[b] Department of Restoration Ecology and Built Environment, Tokyo City University, 3-3-1 Ushikubo-nishi, Tsuzuki-ku, Yokohama 224-8551, Japan

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ABSTRACT

Exergy analysis has been used in various fields to quantify the efficiency of various energy transfer processes. So far, most exergy analyses have been performed by assuming steady-state conditions both for a system of focus and its environment. However, steady-state analyses may idealize a problem too much and thereby limit what we can know about the system, since the assumed system is only a snapshot of a certain condition or moment. In particular, a steady-state exergy analysis is not suitable for analyzing problems where the system has a large heat capacity and problems with varying boundary conditions. To understand the exergy transfer and consumption processes in a system whose transient characteristics are critical, an unsteady-state exergy analysis must be conducted.

This study presents a methodology for unsteady-state exergy analysis that can be used to study heat conduction problems. Governing equations of entropy and exergy to be parallel to the governing equation of energy are derived in their partial differential forms, and their numerical methods are presented in detail. Based on the proposed methodology, an unsteady-state exergy analysis of a heat conduction problem for a concrete wall is carried out to demonstrate its transient exergy behavior.

1. Introduction

Exergy analysis is a method for quantifying the efficiency of a variety of energy transfer processes. Energy analysis, which is generally conducted to examine the efficiency of a system, is based on the first law of thermodynamics that defines the conservation of energy. It expresses the flow and conversion of energy under the law of conservation, but it does not clarify features related to energy quality. The consideration of irreversibility that necessarily accompanies energy transfer and conversion processes has to be based on the second law of thermodynamics, and the introduction of entropy allows for the quantification of irreversibility. Exergy analysis thus considers both the first and second laws of thermodynamics and by introducing the environmental temperature (reference temperature), the relative state of a system can be described. Exergy is the portion of energy that can be converted into work and is defined as the difference between the total energy supplied and the portion that is not converted to work (consumed exergy = anergy); or in other words, exergy is a quantity that indicates how much the ability of dispersion exists in the flow of energy and matter and also in the state of energy and matter relative to the environmental space, in which the system of focus exists.

An advantage of exergy analysis is that it allows us to analyze how efficient the energy conversion is, that is, the quality of the energy transfer process. As Shukuya [1] pointed out, although energy analysis is based solely on the first law of thermodynamics, the term energy “consumption” has been commonly used, but strictly speaking, it is not correct. The well-used term energy consumption usually means the input into a system, and the exergy analysis clarifies what the consumption is. Therefore, it needs to be introduced for the holistic thermodynamic analysis of a system.

Exergy analysis has been used since the 1970s to improve the efficiency of power plants and chemical processes, but its application to heating and cooling systems in buildings and the built environment only commenced quite recently in the 1990s [2,3]. Thus, this field has not matured yet, but it is being actively researched and discussed. In particular, Torío et al. [4] conducted an extensive review regarding various methodologies of exergy analysis and stated that an agreement on the methodology for exergy analysis is necessary.

Taking a full account of thermodynamic descriptions into consideration for the analyses of building facilities is natural and thus, exergy analysis has been mainly used to examine the exergy efficiency of various types of heating and cooling systems [5–14]. These previous studies analyzed the exergy supply, flow, and

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* Corresponding author.
E-mail addresses: wonjun@iis.u-tokyo.ac.jp (W. Choi), ooka@iis.u-tokyo.ac.jp (R. Ooka), shukuya@tcu.ac.jp (M. Shukuya).

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Nomenclature

c	specific heat capacity [J/(kg K)]
C	volumetric heat capacity [J/(m^3 K)]
d	infinitesimal change of in a quantity of state
d′	infinitesimally small amount of generation
k	thermal conductivity [W/(m K)]
K	thermal conductance [W/(m^2 K)]
K_{tot}	total conductance in calculation domain [W/(m^2 K)]
q	rate of heat flux [W/m^2]
Q	internal energy [J/m^3]
R	thermal resistance [m^2 K/W]
s_f	entropy flow [Ons/(m^{3}s) = W/(m^3 K)]
s_g	entropy generation rate [W/(m^3 K)]
S_{st}	stored entropy [J/(m^3 K)]
t	time [s]
T	temperature [K]
T_{BC}	boundary temperature [K]
T_0	reference or environmental temperature [K]
x	x-coordinates [m]
x_c	exergy consumption rate [W/m^3]
x_f	exergy flow [W/m^3]
x_{st}	exergy stored rate [W/m^3]
X_{st}	stored exergy [J/m^3]

Subscripts

i	i-th node
is	inner surface
os	outer surface
$-$	inflow from node $i-1$ to i, or a quantity defined on the left side of node i
$+$	outflow from node i to $i+1$, or a quantity defined on the right side of node i

Superscript

n	n-th time step

Greek letters

α	thermal diffusivity [m^2/s]
ρ	density [kg/m^3]
σ_{fi}	entropy inflow [W/(m^2 K)]
σ_{fo}	entropy outflow [W/(m^2 K)]
σ_g	entropy generation rate [W/(m^2 K)]
σ_{st}	entropy stored rate [W/(m^2 K)]
χ_c	exergy consumption rate [W/m^2]
χ_{fi}	exergy inflow [W/m^2]
χ_{fo}	exergy outflow [W/m^2]
χ_{st}	exergy stored rate [W/m^2]

(All bold characters in the manuscript denote a vector or matrix.)

consumption in subsystems of heating and cooling systems under steady-state assumptions. Through the exergy analysis, the characteristics of transfer processes that cannot be found by energy analysis alone are clarified. It helps to identify the inefficient parts of the system and draw a map that shows how exergy is supplied, distributed, and consumed within the system [15–17]. System optimization by using exergy analysis leads to thermodynamic optimization or minimization of entropy generation [18].

Recently, the concept of exergy has been used as a control criterion for heating and cooling systems. Yin et al. [19] analyzed four different pump control strategies of a chilled water circuit from the exergy viewpoint. Razmara et al. [20] implemented a model predictive control with the objective function of minimizing the exergy consumption rate. This control strategy resulted in a 22% reduction in exergy consumption and a 36% reduction in electrical energy use compared to a conventional rule-based control approach.

Additionally, studies on the configuration of building envelopes have been conducted. The building envelope determines the indoor thermal environment and thus has a great influence on human thermal comfort and exergy consumption [21,22]. Schweiker and Shukuya [23] investigated the effect of improving the building envelope and occupant behavior on exergy consumption. The improvement of the building envelope was found to be a more effective option than changes in the occupant behavior when the weather conditions were unfavorable to thermal comfort, but the occupant behavior had a bigger influence than the insulation when the weather conditions were moderate. Dovjak et al. [24] analyzed the changes of exergy flow patterns due to improvements to the building envelope, and the analysis was extended to better understand interactions between building systems and the human body. Shukuya [25,26] conducted an exergy analysis on a building envelope and window system. For this analysis, exergy equations for three different transfer modes, i.e., radiation, convection, and conduction, were formulated. The direction of exergy flow and occurrence of warm or cool exergy that depended on the relationships among the inner and outer surface temperatures and environmental temperature were systematically analyzed.

All of the above-mentioned studies were conducted under the assumption of a steady-state. Steady-state analysis is a meaningful task to capture the overall characteristics of a system, but it can be overly ideal and the results will just represent a snapshot of certain conditions or a particular moment. Especially, steady-state analysis is not sufficient for analyzing problems where a system has a large heat capacity and dynamically changing boundary condition. In such cases, an unsteady-state exergy analysis should be conducted to understand the transient exergy processes of a system.

Although the need for unsteady-state exergy analysis has been pointed out [4], only a few related studies could be found. Angelotti et al. [27,28] compared the results from steady and dynamic exergy analyses of heating and cooling systems in two different Italian climates. Their analyses showed that the difference between the dynamic and steady approaches was significant in the cooling season and under the condition of intermittent system operation. However, the “dynamic” exergy analysis they employed was not a complete form of an unsteady-state exergy analysis that can consider transient exergy processes, because their study was based on the steady-state formulas and only changed the environmental temperature hour by hour by using weather data.

When energy is transferred by heat conduction, transient exergy processes may become important. In such a case, due to the small thermal diffusivity, exergy flows and storage may become “warm” exergy or “cool” exergy depending on the variations of both the system temperature and environmental temperature. A typical example in everyday life is the energy and exergy processes in a building envelope. In general, the building envelope has a low thermal diffusivity and the exergy process changes dynamically according to the relationships among the environmental temperature, inner and outer surface temperatures, temperature distribution inside the envelope, and indoor air temperature. Therefore, for the analysis of such a system, conducting an unsteady-state exergy analysis should be able to give a better understanding of the system behavior. However, to the best of our knowledge, such an unsteady-state exergy analysis has not been attempted so far and a methodology has not been proposed yet, though a crude trial was made by Shukuya [29].